

General relativistic simulations of compact binary mergers as engines of short gamma-ray bursts

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Abstract. Black hole - neutron star (BHNS) and neutron star - neutron star (NSNS) binaries are among the favored candidates for the progenitors of the black hole - disk systems that may be the engines powering short-hard gamma ray bursts. After almost two decades of simulations of binary NSNSs and BHNSs in full general relativity we are now beginning to understand the ingredients that may be necessary for these systems to launch incipient jets. Here, we review our current understanding, and summarize the surprises and lessons learned from state-of-the-art (magnetohydrodynamic) simulations in full general relativity of BHNS and NSNS mergers as jet engines for short-hard gamma-ray bursts.

1. Introduction

The LIGO and Virgo collaborations recently announced the detection of two gravitational wave signals that were consistent with the inspiral and merger of binary black hole systems [3, 2]. A third signal, also consistent with a binary black hole, was announced but was not significant enough to be classified as a detection [2]. These observations are milestones in the field of gravitational physics because they confirmed for the first time the validity of general relativity in the strong-field, dynamical regime, they provided the cleanest evidence for the existence of black holes and binary black holes, and gave us hints on plausible formation scenarios for such systems. Most importantly, these spectacular detections opened up a new window to observing our Universe, and marked the onset of the era of gravitational wave (GW) astronomy. Over the next few years, advanced LIGO is anticipated to reach its design sensitivity and advanced VIRGO will join the observations. As a result many more GW signals are anticipated to be detected, and not only from other black hole binaries, but also from the inspiral and merger of neutron star–neutron star (NSNS) and black hole–neutron star (BHNS) binaries.

Coalescing NSNSs and BHNSs are not only sources of GWs, but also of electromagnetic (EM) signals counterpart to the GWs that can arise both before [87, 113, 137, 132, 145, 119] and after [117, 116] the GW peak amplitude. Detecting both GW and EM signals that are generated from the same source would provide a wealth

of information about the source, and allow novel tests of relativistic gravitation and fundamental physics[‡] GWs can also constrain the NS equation of state (EOS) (see e.g. [100, 13] for recent work and references therein), and combination of GWs with EM signals can help explain where r-process elements in the Universe may form [156], and even allow for an accurate and model-independent computation of the Hubble constant, and hence constrain dark energy models [128]. In fact, performing several of the aforementioned tasks may actually *require* an EM counterpart to the GW signal. For example, if gravity behaves phenomenologically as in some scalar-tensor theory models, where the deviations from general relativity (GR) may show only near merger, degeneracies with the equation of state cannot be lifted by GWs alone, whereas even partial information from EM counterparts can lift the degeneracy [144].

Detection of GW, EM and/or potentially even neutrino signals from the same source would mark the onset of the era of “multimessenger” astronomy. However, the interpretation of multimessenger signals from compact binary mergers will depend crucially on our theoretical understanding of these events, which in turn requires simulations in full relativistic gravitation to treat the strong, dynamical fields and high velocities that naturally arise in these mergers.

Among all types of EM signatures NSNSs and BHNSs are thought to be able to generate, a short gamma-ray burst (sGRB) is the one these systems are best known. It has long been hypothesized that mergers of these compact binaries can form the engine that may power an sGRB - an accretion disk onto a spinning black hole [57, 126, 120, 140, 114, 102, 125]. Advances in observations of sGRBs which led to the identification of their host environments indicate that the progenitors of sGRBs are mainly associated with elliptical galaxies and stem from an old, evolved population of stars [71, 24]. This makes the case of NSNSs and BHNSs being the progenitors of sGRBs even more compelling. Association of a sGRB with a GW signal consistent with the inspiral and merger of a BHNS or NSNS system (perhaps the holy grail of “multimessenger” astronomy) would solidify the compact binary coalescence model of sGRBs. However, the bulk of sGRBs have been found at redshifts $z > 0.1$ [24], i.e., at luminosity distances $D_L \gtrsim 460$ Mpc (assuming standard Λ CDM cosmology) and hence outside the aLIGO NSNS horizon. Also the most recent estimates of sGRB rates suggest a rate of 8/yr [72] within the aLIGO NSNS horizon of ~ 200 Mpc \S . Thus, a solid identification of an sGRB with a GW signal may require either several years of LIGO/Virgo observations or a lucky nearby sGRB that happens to point toward the Earth. However, as rate estimates typically have substantial uncertainties, we might even have to wait for third-generation GW observatories until such an identification

[‡] Tests of relativistic gravitation with GW astronomy is an entire topic by itself, which will not touch upon in this review, but for some recent work and reviews see e.g. [193, 192, 38, 105, 187, 34, 194, 9, 161, 173, 144, 26, 32, 195, 45, 78, 16, 165, 150, 190, 191, 29, 1] and references therein.

[§] The aLIGO BHNS horizon with masses $10M_\odot$ for the BH and $1.4M_\odot$ for the NS is ~ 900 Mpc, but unless the BH is rapidly spinning or the NS is sufficiently puffy these systems may not be able to power sGRBs (see Sec. 3.1 below).

may be possible. But, until this happens, a theoretical/computational study of compact binary mergers with the aid of numerical relativity is an important avenue to gaining a better understanding of these systems as jet engines for sGRBs and for inferring intrinsic properties/parameters of the engines from EM observations alone.

Recent years have witnessed a growing number of compact binary simulations in full general relativity with different levels of sophistication and realism. Although these simulations have contributed to improving our understanding of BHNS and NSNS mergers, we are still far away from constructing a complete theoretical/computer generated sGRB model starting from the inspiral and merger all the way to jet acceleration and emergence of the gamma-ray burst. The existence of such a model would solidify compact binary mergers as viable sGRB engines on theoretical grounds, and would, in principle, allow for the extraction of the progenitor binary parameters from the gamma-ray signal even in the absence of a GW counterpart. Moreover, a complete theoretical model of sGRBs would dictate the time lag between the peak GW amplitude and the gamma-ray burst, and thereby would better inform triggered GW searches. However, it is hard to envision that such an sGRB model is achievable in the foreseeable future because of the very high-resolution requirements to capture the relevant magnetic effects, the disparity of length and time scales involved in the problem and because of the very difficult neutrino transport problem involved following merger. For now, it seems that the combination and coupling of different codes simulating different phases of the evolution of an sGRB engine offer the only plausible route for building such a complete model of an sGRB. But, even this approach is several years away from being realized.

There exists a vast literature on theoretical/computational methods for modeling the different phases of an sGRB engine, however, here, we will focus on the very first stage, i.e., the formation of the BH-disk engine from the inspiral and merger of compact binaries involving neutron stars and the early launch of jets. This phase of the sGRB engine requires the field of numerical relativity, and hence this review is centered on the status of state-of-the-art (magnetohydrodynamic) simulations of compact binary mergers as sGRB engines. Since there exists only little work on simulations of compact binaries with a neutron star component in modified gravity theories [15, 131, 173, 144], the focus of this review will be on simulations in full GR, and in particular we will highlight the latest developments in this subfield.

The remainder of the paper is structured as follows. In Section 2 we review the computational challenge involved in modeling compact binaries and discuss the equations that govern their dynamical evolution; in Sec. 3 we review recent results obtained from state-of-the-art simulations of binary BHNSs and in Sec. 4 recent results from state-of-the-art simulations of binary NSNSs. We conclude in Sec. 5 with a brief discussion and list of open questions. Unless otherwise specified, below we adopt geometrized units, where $G = c = 1$.

2. The challenge

The NSNS and BHNS inspiral and merger problem is a multi-scale and multi-physics one. The range of length and time scales in the problem in conjunction with the large number of non-linear partial differential equations one must solve, makes modeling these binaries a very challenging task.

2.1. Length and time scales

The range of length and times scales involved in this problem spans over 3-4 orders of magnitude. For example, to reliably model the inspiral over the last few orbits and to resolve the neutron star(s) and/or black hole requires at least 100 grid points across the radius of each object. This implies that for a typical NS with radius $\sim 10\text{km}$, the grid spacing must be $\Delta x \sim 0.1\text{km}$. However, computing reliable gravitational waveforms, requires that the GW extraction be done at a radius of $\sim 100M \sim 450(M/3M_\odot)\text{km}$ or greater. Here M is the binary total mass. To properly capture hydromagnetic effects during an NSNS merger and in the post-merger BH-disk system that forms, a grid-spacing of order 10m seems to be necessary [196, 93, 95]. In other words, the length scales span 3-4 orders of magnitude from inspiral through merger. Therefore, some level of mesh refinement is necessary, and all modern numerical relativity codes adopt adaptive mesh refinement. If a jet emerges shortly after merger, tracking its evolution until it achieves terminal Lorentz factor, requires that one be able to follow the jet to distances of several hundreds of thousands to millions of M from the engine, where the jet may typically reach its terminal Lorentz factor (see e.g. [181]). The sparsity of length scales demonstrates quite clearly how difficult it becomes to model an sGRB from first principles, but see [50] for a method that can be used if the jet decouples from the central engine, which occurs when the jet becomes supersonic.

Some fundamental time scales involved in the BHNS problem are the timestep, NS dynamical time scale, the inspiral time scale from the initial orbital separation, and the incipient jet emergence time scale.

Due to the Courant limitation, the timestep must be of order $\Delta t \simeq 0.5\Delta x \simeq 1.5 \times 10^{-4}(\Delta x/100\text{m})$ ms. The NS dynamical time scale is

$$t_d = 2\pi \sqrt{\frac{R_{\text{NS}}^3}{M_{\text{NS}}}} \simeq 0.5 \left(\frac{R_{\text{NS}}}{10\text{km}} \right)^{3/2} \left(\frac{M_{\text{NS}}}{1.35M_\odot} \right)^{-1/2} \text{ms}, \quad (1)$$

where R_{NS} is the NS radius and M_{NS} the NS mass.

The inspiral time to merger from an initial orbital separation is dictated by the gravitational wave time scale, which in the quadrupole approximation is given by

$$t_{\text{merge}} = \frac{5}{16} \frac{a^4}{M^3 \zeta} \simeq 3000 \left(\frac{a}{10M} \right)^4 \zeta^{-1} M \simeq 45 \left(\frac{a}{10M} \right)^4 \left(\frac{M}{3M_\odot} \right) \zeta^{-1} \text{ms} \quad (2)$$

where a is the orbital separation, $\zeta = 4\eta = 4q/(1+q)^2$, with η the symmetric mass ratio, and $q = M_1/M_2$ the usual binary mass ratio. Note, that for an equal-mass binary $\zeta = 1$.

The jet emergence time is of order $100(M/3M_\odot)$ ms after merger [140] and could be longer (see below). Thus, evolving from inspiral through jet launching, requires a total evolution of $\sim 100 - 150$ ms, which implies that of order 10^6 time steps are not atypical in these simulations.

In an NSNS merger scenario, a BH may not form immediately after merger, and instead, a differentially rotating hypermassive neutron star (HMNS) may be the merger outcome. A HMNS is a transient object. It will undergo “delayed collapse” on a secular time scale (see e.g. [19, 47]), and then form the BH-disk engine that may power a sGRB. An HMNS is supported against collapse by a combination of the additional centrifugal support due to differential rotation and the extra thermal pressure generated by shock heating (see e.g. [164, 141]). The BH-disk system will then likely form on an Alfvén time t_{Alf} (the time scale for the braking of the differential of the HMNS by magnetic fields [166]) or the GW time scale (the time over which angular momentum is carried away through GW emission from a non-axisymmetric HMNS) t_{GW} , and possibly even the cooling time t_ν due to neutrino emission [164]. These time scales are given by [141]

$$t_{\text{Alf}} \approx 30 \left(\frac{R}{20\text{km}} \right)^{-1/2} \left(\frac{M}{2.8M_\odot} \right)^{1/2} \left(\frac{B}{10^{15.5}\text{G}} \right)^{-1} \text{ms}, \quad (3)$$

where R is the characteristic radius of the HMNS, M the mass of the HMNS, which approximately equals the total mass of the NSNS, and B a typical value of the magnetic field strength of the HMNS. The GW time scale is

$$t_{\text{GW}} \approx 200 \left(\frac{e}{0.75} \right)^{-2} \left(\frac{R}{20\text{km}} \right)^4 \left(\frac{M}{2.8M_\odot} \right)^{-3} \text{ms}, \quad (4)$$

where e is the HMNS ellipticity and where we adopted a value of a plausible bar-like configuration. The estimated t_{GW} is comparable to the GW time scale inferred by numerical relativity NSNS simulations (see e.g. [154]). Finally, the cooling time scale is estimated as follows (see also [158] for an estimate accounting for trapping effects in deformed objects)

$$t_\nu \approx 1 \left(\frac{M}{2.8M_\odot} \right) \left(\frac{R}{20\text{km}} \right)^{-1} \left(\frac{E_\nu}{15\text{MeV}} \right)^2, \quad (5)$$

where E_ν is the rms energy of the emitted neutrinos. Thus, if the HMNS is primarily supported by thermal pressure, as has been argued to be the case in a simulation in [164], one may need to evolve for 1s to form the BH disk engine in NSNS merger scenario, which implies of order 10^7 timesteps. As a result, numerical relativity studies of BH formation in NSNS mergers have focused only on cases where a BH forms within ~ 100 ms following merger (see Appendix of [154] for the longest NSNS hydrodynamic simulation in full GR).

2.2. Equations

The multi-scale nature of the inspiral and merger problem of compact binaries is one aspect of the challenge numerical relativity simulations face. The multi-physics nature of the problem is another one. Moreover, compact objects are inherently relativistic,

requiring that these simulations be performed in full general relativity, and thereby complicating the task of the modeler even further. The term “multi-physics” implies that a large number of equations must be solved. In particular, the equations describing compact binaries involving neutron stars are (see e.g. [18]) the following:

a) The Einstein equations which govern the evolution of the spacetime, and are given by

$$G_{\mu\nu} = 8\pi T_{\mu\nu}, \quad (6)$$

where $G_{\mu\nu}$ is the Einstein tensor and $T_{\mu\nu}$ the matter stress-energy tensor. The Einstein equations are 10 second-order, non-linear partial differential equations (PDEs).

b) The energy-momentum and radiation transport equations which govern the evolution of the matter and radiation and are given by

$$\nabla_\mu T^{\mu\nu} = -\nabla_\mu R^{\mu\nu}, \quad (7)$$

$$\nabla_\mu R^{\mu\nu} = -G^\nu, \quad (8)$$

where $R_{\mu\nu}$ is the radiation stress tensor and G^ν the radiation four-force density. These form a set of another 8 PDEs.

c) Maxwell’s equations which govern the evolution of the electromagnetic fields, and are given by

$$\nabla_\mu F^{\mu\nu} = -4\pi J^\nu, \quad (9)$$

$$\nabla_\mu {}^*F^{\mu\nu} = 0, \quad (10)$$

where $F_{\mu\nu}$ is the electromagnetic tensor and ${}^*F^{\mu\nu}$ its dual. Maxwell’s equations add another 8 PDEs.

d) The baryon number conservation (or continuity) equation

$$\nabla_\mu (\rho_0 u^\mu) = 0. \quad (11)$$

These add up to a total of 27 coupled PDEs in 3 spatial plus 1 temporal dimensions. In fact, the radiation transport equation has an additional 3 dimensions (two angular and the radiation frequency) making it a 6+1 dimensional problem. This system of equations must also be supplemented with a microphysical, hot, nuclear EOS and, in the general case, with an Ohm’s law for the current, which both add even more to the complexity of the problem. Note that the above counting does not even account for the lepton number conservation equations nor does it account for the fact that these equations are not in a form amenable for numerical integration, and that standard formulations of these equations used in numerical simulations involve many more coupled PDEs (see e.g. [6, 30, 18, 85, 168] for textbooks).

The large number of non-linear coupled equations is not the only challenge a numerical relativist faces. Other unique challenges involve curvature singularities (infinities) that one must treat properly when modeling BH spacetimes, and that in general relativity only gauge independent quantities are meaningful, which makes extracting physical information from these simulations a non-trivial task. However, many of these difficulties have been overcome over the years by creative theoretical

and computational methods. For a comprehensive description of such methods see [6, 30, 18, 85, 168]. Multiple codes have been developed that solve the full Einstein equations coupled to all or a subset of the remaining equations adopting various degrees of realism and approximations [49, 79, 63, 64, 69, 163, 182, 94, 56, 130, 107, 42, 75, 40, 149, 127, 123, 74, 61]. These codes have been applied to the study of both BHNS and NSNS mergers.

3. BHNS mergers

It has been about 10 years since hydrodynamic simulations of BHNS mergers in full general relativity have become routine [20, 180, 67, 66, 176, 59]. BHNS simulations combine all the physical challenges encountered in magnetohydrodynamics, such as magnetized shock discontinuities, with those of vacuum black holes, namely a curvature singularity. The latter is the primary reason why the advancement of BHNS simulations lagged compared to NSNS simulations, and were made possible only after the breakthrough BHBH vacuum simulations of [147, 14, 33]. For a comprehensive review surveying BHNS simulations see [172]. Here we only review studies of these systems in full GR and only relevant to sGRBs.

3.1. Hydrodynamic Simulations

Primordial BHNS binaries are likely quasicircular because GW emission tends to circularize the orbit [143]. These binaries are also anticipated to involve irrotational neutron stars, because the tidal synchronization time scale exceeds the inspiral time scale [27].

Motivated by the above conclusions, the first studies of BHNS mergers testing the viability of BHNSs as sGRB engines, focused on hydrodynamic simulations of quasicircular, irrotational binaries, with the goal of determining the parameter space within which an appreciable accretion disk may form outside the BH following the NS tidal disruption. Having a BH-disk remnant is important to power an sGRB because even a small fraction of the accretion power can account for typical sGRB luminosities. The characteristic sGRB durations and luminosities dictate the amount of matter that an accretion disk should have as follows: Assuming an efficiency ϵ for converting the accretion luminosity $\dot{M}c^2$ to gamma-ray luminosity L_γ , the matter accretion rate onto the BH engine becomes $\dot{M} = \epsilon^{-1}L_\gamma/c^2$. The disk lifetime, which provides the sGRB fuel, should be of order the typical sGRB duration t_{sGRB} [102]. Thus, the disk mass can be estimated as $M_{\text{disk}} \sim \dot{M} \times t_{\text{sGRB}}$, yielding

$$M_{\text{disk}} \sim 0.1M_\odot \left(\frac{\epsilon}{0.01}\right)^{-1} \left(\frac{L_\gamma}{10^{51}\text{erg/s}}\right) \left(\frac{t_{\text{sGRB}}}{2\text{s}}\right) \quad (12)$$

Hence, $\sim 8\%$ of the NS rest mass (assuming $M_{\text{NS}} = 1.3M_\odot$ and 1% efficiency) should remain outside the BH following merger, in order to power a 2s-long, 10^{51} erg/s sGRB

(the upper end on duration of sGRBs). However, the average sGRB duration is 0.3s [99], thus a $\sim 0.015M_\odot$ disk suffices for most cases.

But, forming a disk outside the BH is not trivial, because for this to occur the NS must be tidally disrupted outside the BH's innermost stable circular orbit (ISCO). To understand why this is difficult one can derive an order of magnitude estimate for the tidal disruption radius a_d of the NS by equating the BH tidal force to the NS gravitational force on the NS surface [60], which yields

$$\frac{2M_{\text{BH}}R_{\text{NS}}}{a_d^3} \simeq \frac{M_{\text{NS}}}{R_{\text{NS}}^2} \implies \frac{a_d}{M_{\text{BH}}} \simeq 3\left(\frac{C}{0.2}\right)^{-1}\left(\frac{q}{7}\right)^{-2/3}, \quad (13)$$

where $C = M_{\text{NS}}/R_{\text{NS}}$ is the NS compaction, and $q = M_{\text{BH}}/M_{\text{NS}}$ the BH to NS mass ratio and a value of 7 was adopted since it is anticipated to be the most probable value for primordial BHNS binaries [23]. Recall that the ISCO radius is $6M_{\text{BH}}$ for a non-spinning BH, M_{BH} for a maximally spinning BH and $3M_{\text{BH}}$ for a BH with dimensionless spin parameter $\chi = a_{\text{BH}}/M_{\text{BH}} \sim 0.78$ [17]. The simple Newtonian estimate of Eq. (13) demonstrates how difficult it is to disrupt a NS outside the ISCO of a slowly spinning BH. Therefore, an appreciable disk may form following the NS tidal disruption only for relatively small mass ratios and either if the BH is highly spinning and/or the NS is not very compact (smaller C).

Multiple numerical relativity investigations have studied how much matter remains outside the BH following a quasicircular, irrotational BHNS merger, and the results were compiled in [73], where the following EOS-independent fitting formula was proposed for predicting the mass M_{disk} left outside the BH to form a disk that may power a sGRB

$$\frac{M_{\text{disk}}}{M_{\text{NS}}} = 0.415q^{1/3}(1 - 2C) - 0.148R_{\text{ISCO}}/R_{\text{NS}}, \quad (14)$$

where R_{ISCO} denotes the ISCO radius of the initial BH. However, note that the applicability of this formula is restricted to dimensionless BH spins $\chi \lesssim 0.9$ [108]. Using Eq. (14) one can plot contours of disk mass as a function of compaction, and BH spin for a given mass ratio. This is shown in Fig. 1 for the most probable value of the mass ratio for primordial BHNS binaries [23]. The main conclusion drawn from Fig. 1 is that *at “realistic” mass ratios and values of the NS compaction of $C = 0.18$ suggested by observations [177], the disk mass will be $\gtrsim 0.1M_\odot$ only if the BH dimensionless spin is $\chi \gtrsim 0.8$, which could be a very tight constraint.*

The previous conclusion holds for quasicircular BHNSs in which the NS is irrotational. While quasicircular binaries probably dominate the BHNS merger rates in the Universe, some recent results [98, 103, 162] indicate that in dense stellar regions, for example galactic nuclei and globular clusters (GCs), compact binaries can form through single-single (dynamical capture) and binary-single (exchange) interactions, and merge with substantial eccentricities. Rates of these eccentric mergers are highly uncertain, but the optimistic ones can be up $\sim 100\text{yr}^{-1} \text{ Gpc}^{-3}$ [178, 55], i.e., comparable to the lower bound on the estimated merger rate for primordial binaries [90, 39]. Another important aspect of GC neutron stars is that more than 80% of pulsars residing in GCs

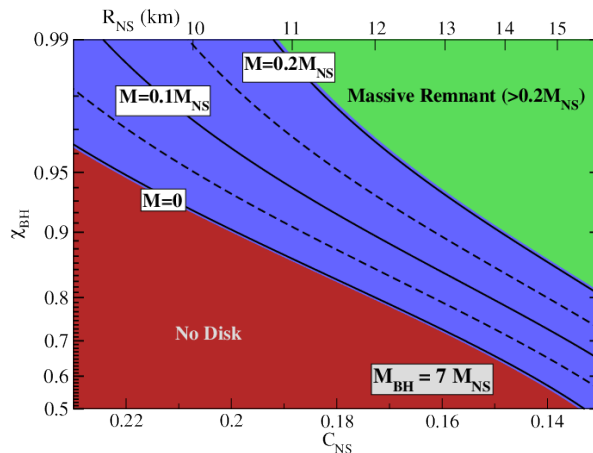


Figure 1. Contours of disk mass left outside the BH following a BHNS merger at fixed mass ratio $q=7$. Here C_{NS} is the NS compaction and χ_{BH} the BH dimensionless spin. The NS radius shown on the top horizontal axis assumes a NS gravitational mass of $1.4M_{\odot}$. Figure 7 from [73].

have periods less than 10 milliseconds (i.e. are millisecond pulsars), and hence compact binary mergers with at least one neutron star component occurring in GCs could involve rapidly spinning neutron stars [51, 135, 53]. High NS spin makes the star less bound, increasing the tidal disruption radius, and both prograde rapid NS spin and orbital eccentricity move the effective innermost stable orbit (ISO) inward allowing for the NS to be tidally disrupted outside the ISO even when a non-spinning BH is involved.

Motivated by the above, hydrodynamic simulations in full GR of dynamical capture BHNS mergers have been performed in [178, 55] with non-spinning NSs and in [51] with spinning NSs for $q = 4$. Depending on the value of the periaapse distance during the final encounter, the amount of disk mass for non-spinning BHs found ranges from $\sim 1\% - 10\%$ of the NS rest mass for moderate stiffness EOSs ($C = 0.17$), and it can be up to 15% for stiff EOSs ($C = 0.13$). By contrast, Eq. (14) for a $q = 4$ quasi-circular BHNS predicts no mass outside the BH for $C \gtrsim 0.135$ and only 2.6% for $C = 0.13$. Therefore, dynamical capture BHNS mergers as may arise in GCs are viable progenitors for sGRBs and can potentially generate BH-disk engines more easily than quasi-circular mergers with the same BH:NS mass ratio and initial black hole spin.

Showing that a compact binary system can form a BH-disk engine is the first step in demonstrating theoretically the viability of compact binaries as progenitors of sGRBs (in the hyperaccreting and jet-launching BH model). The second crucial step is to show that these BH-disk engines can launch jets that can be accelerated to a Lorentz factor $\Gamma_L \gtrsim 100$, which is a crucial ingredient in the fireball model of sGRBs [114]. The most popular mechanisms invoked for launching and accelerating jets are either magnetic fields [28] or neutrino annihilation [121, 7], but it also could be that a combination of the two is necessary. Most simulations in full GR to date have focused on the magnetic launching mechanism mainly because the neutrino annihilation mechanism requires proper treatment of the neutrino transport equation which is far from an easy

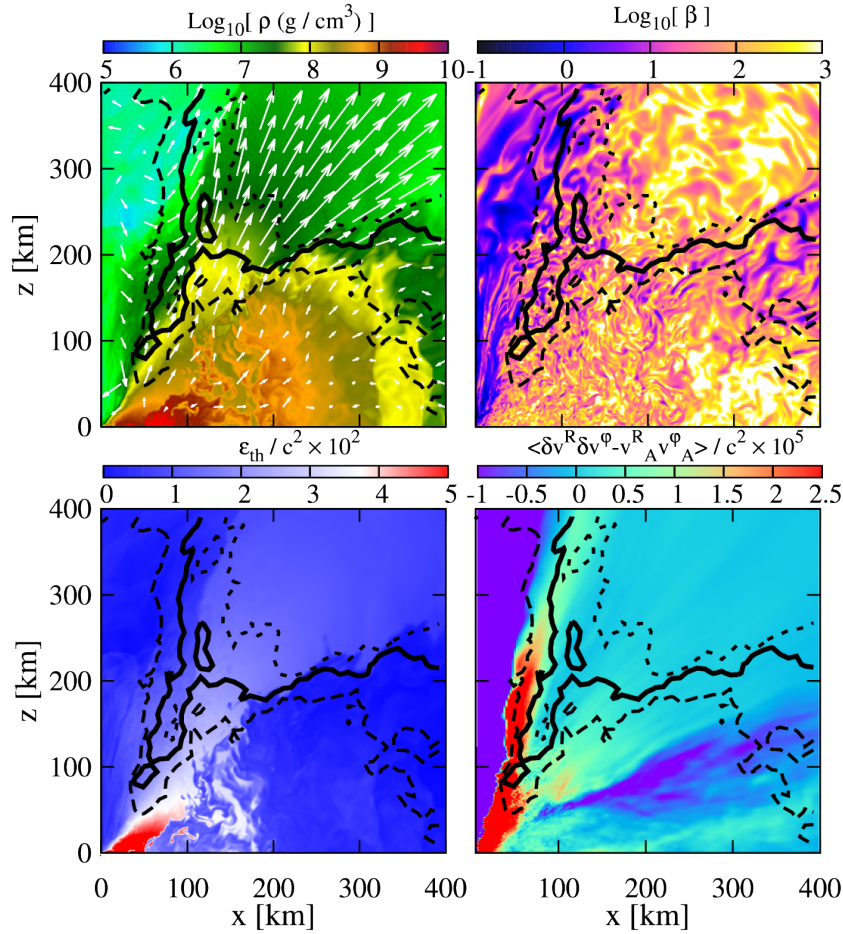


Figure 2. Top left: rest-mass density with velocity arrows. A wind outflow is observed, but no collimated outflow is found within funnel walls formed by the wind. Top right: plasma beta parameter. Bottom left: thermal specific internal energy. Bottom right: sum of Maxwell and Reynolds stress (bottom-right). All profiles are shown on the $x-z$ plane at $t \sim 50$ ms. Figure 5 from [95].

task. Therefore, next we will summarize the status of magnetohydrodynamic simulations of BHNS mergers in full GR.

3.2. Magnetohydrodynamic Simulations

The combination of a spacetime singularity, hydrodynamic shocks and the presence of magnetic fields renders simulations of BHNS systems extremely challenging. As a result only few magnetohydrodynamic (MHD) simulations of BHNS systems in full GR have been performed to date.

The MHD simulations in full GR performed in [35] reported the formation of a viable BH-disk engine, but no jets were found. The studies of magnetized BHNS mergers in full GR as sGRB engines carried out in [62, 65] probed an expanded part of the BHNS parameter space. The most promising case in terms of the amount of disk mass left outside the BH was a 3:1 mass ratio with an initially spinning BH $\chi = 0.75$. This

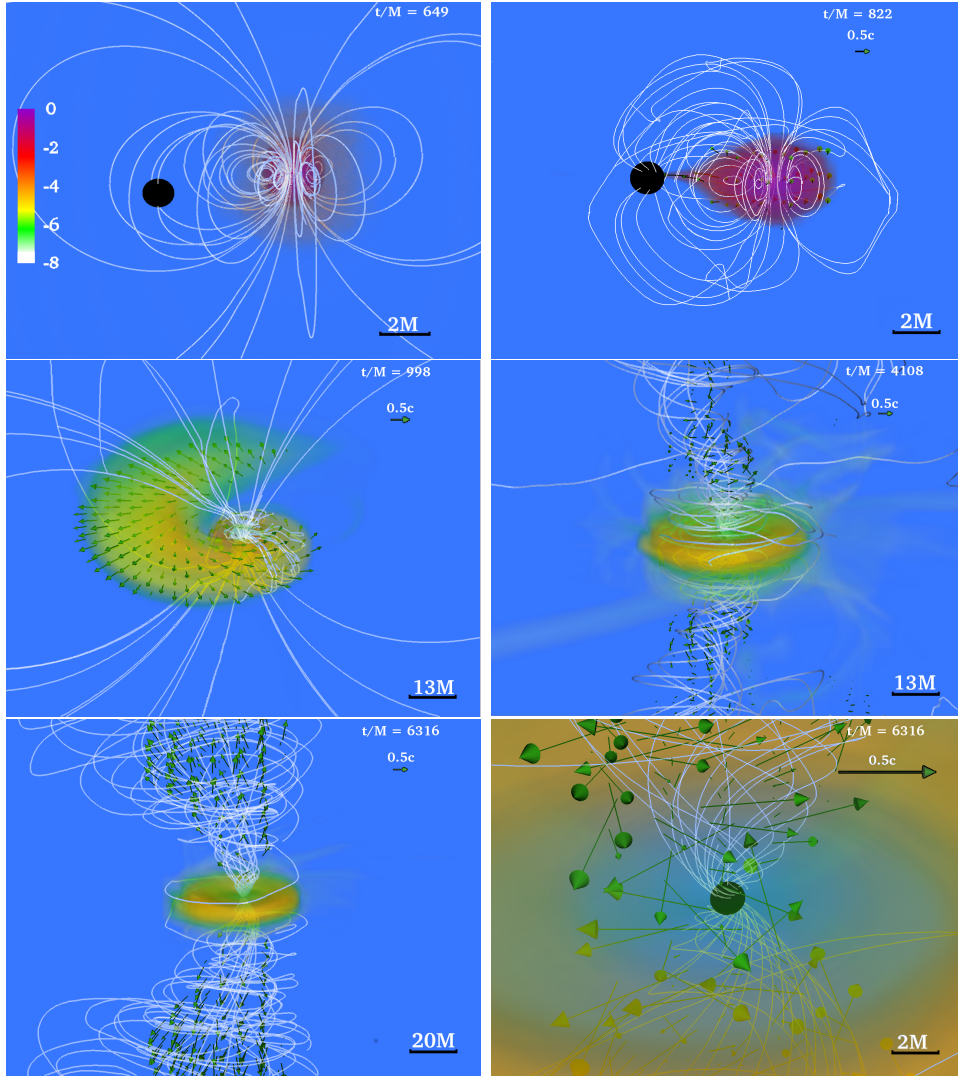


Figure 3. Volume rendering of the rest-mass normalized to its initial maximum value $\rho_{0,\text{max}} = 8.92 \times 10^{14} (1.4M_{\odot}/M_{\text{NS}})^2 \text{g cm}^{-3}$ (log scale) at select times. Arrows indicate matter velocities and white lines the magnetic field lines. The bottom panels show the system after an incipient jet has been launched. Here, $M = 2.5 \times 10^{-2} (M_{\text{NS}}/1.4M_{\odot}) \text{ms} = 7.58 (M_{\text{NS}}/1.4M_{\odot}) \text{km}$. Figure 1 from [140].

configuration results in $\sim 10\%$ of the initial neutron star rest mass forming an accretion disk around the remnant BH with dimensionless spin of ~ 0.85 . In these studies the initial neutron star was seeded with a dipole magnetic field confined entirely in the interior of the star and equatorial symmetry was imposed during the evolution. The results about jet emergence were null, even when the strength of the initial magnetic field seeded in the NS was much stronger when compared to standard inferred values of pulsar magnetic fields. The initial explanation for the lack of a jet was that the resolution was too low to resolve the wavelength of the fastest growing mode of the magnetorotational instability (MRI) in the resulting disk. However, even when lifting the equatorial symmetry and increasing the resolution to resolve the MRI wavelength

by 10 grid points – the rule of thumb for capturing the basic magnetic field growth due to MRI [170] – again no jet emerged.

Similar results were reported in [95] who performed MHD simulations of BHNSs in full GR adopting higher resolution. The initial configuration consisted of a quasiequilibrium binary, with an irrotational NS of mass $1.35M_{\odot}$, mass ratio $q = 4$, and BH spin $\chi = 0.75$. At $t = 10$ ms after merger a BH-disk system forms with $\sim 0.13M_{\odot}$ in the disk. But, after ~ 50 ms of evolution the authors of [95] found no jets. However, they reported a wind outflow (see Fig. 2), and the emergence of a large scale, poloidal component of the magnetic field.

The lack of jets from these BHNS simulations was very puzzling and came as a surprise, because for over 15 years GRMHD accretion studies onto BHs in fixed spacetime demonstrated that jets naturally arise in these scenarios (see e.g. [4] for a review). However, as it turns out this is not always the case.

For a magnetized accretion disk with magnetic fields initially confined in the disk interior, a jet can be launched and sustained only if the initial magnetic field is such that a net poloidal magnetic flux is accreted onto the BH [22]. For example, starting with purely toroidal magnetic fields in the disk no jets are launched. This result naturally explains why no jets were found in [62, 65]. In particular, following tidal disruption of the NS by the BH, the bulk of the magnetic field flux flows instantaneously into the BH, and the magnetic field remaining outside is wound into an almost purely toroidal configuration. In addition, the residual poloidal component of the magnetic field in the disk does not have a consistent vertical sign in the sense of [22], hence no jets can be launched.

The missing ingredient for jet launching was finally identified in [140], who made the realization that all early GRMHD BHNS studies used magnetic fields confined in the interior of the NS. Pulsars suggest that a more realistic magnetic field configuration is a dipole extending from the NS interior out to the exterior [140]. While it appears this would be a trivial change, it is not, because it is very challenging to adopt an ideal MHD code to evolve regions where the magnetic field energy density dominates over the rest-mass energy density, as in a pulsar magnetosphere. To overcome this obstacle, the authors designed novel initial conditions, which would capture only one aspect of a magnetosphere, namely magnetic-pressure dominance, but not magnetic-energy density dominance. These new initial conditions allowed the evolution of exterior magnetic fields with an ideal GRMHD code and using a sequence of simulations from weakly to highly magnetic-pressure dominated exteriors, the authors were able to test whether their results were invariable in this sequence.

Following the above approach the authors followed the BHNS encounter through tidal disruption and BH-disk formation. As in the past the magnetic field in the disk interior was predominantly toroidal. However, the no-go conditions for jet launching of [22] could now be evaded because of the existence of an exterior magnetic field. In particular, a poloidal magnetic field component was present throughout the evolution (see Fig. 3). The authors reported that soon after the violent accretion episode and disk

settling, the magnetic field above the BH poles was amplified from $\sim 10^{13}$ G to $\sim 10^{15}$ G primarily via winding [see Eqs. (16), (18) below for an argument of why such magnetic-field strengths arise naturally when jets are launched following compact binary mergers]. This strong magnetic field finally drove an incipient jet about ~ 100 ms following the BHNS merger (see Fig. 3). The result was the same for all magnetospheric conditions ranging from moderate to high magnetic-pressure dominance (magnetospheric plasma parameter $\beta_{\text{ext}} = P_{\text{gas}}/P_{\text{mag}} \in [0.01, 0.1]$), with larger initial β_{ext} resulting in delayed jet launching. The disk lifetime found was 0.5 s, and the jet Poynting luminosity 10^{51} erg/s, which are both entirely consistent with typical sGRBs. The Poynting luminosity was also consistent with the Blandford-Znajek (BZ) power [183]

$$L_{\text{BZ}} \approx 10^{51} \left(\frac{\chi}{0.85} \right)^2 \left(\frac{M_{\text{BH}}}{5.6 M_{\odot}} \right)^2 \left(\frac{B_{\text{BH}}}{10^{15} \text{G}} \right)^2 \text{erg/s}, \quad (15)$$

where B_{BH} is the characteristic value of the magnetic field on the BH horizon, and the other parameters are normalized to values from the simulations of [140].

Jet launching requires a near force-free environment, and how close to force-free an environment is, is indicated by the magnetization parameter $B^2/8\pi\rho c^2$. In a sense the magnetization plays the role of the jet trigger. Consistent with this concept, the jet found in [140] was launched around the time where $B^2/8\pi\rho c^2 \gtrsim 10$. The characteristic Lorentz factors found in the expanding, collimated outflow at the end these simulations were only mildly relativistic ($\Gamma_L \sim 1.3$). However, when the incipient jet was fully developed its magnetization was $B^2/8\pi\rho c^2 \sim 100$. This was a very important finding, because terminal Lorentz factor of a magnetically-powered, axisymmetric jet is set by and approximately equals this number [189]. Hence, in principle, the incipient jets found in [140] can be accelerated to Lorentz factors required to explain sGRB phenomenology. Finally, these calculations furnished the first computation of the delay time between the GW peak amplitude and the EM signal.

While these results were obtained assuming initially strong magnetic fields, they were still dynamically unimportant ($\beta \geq 20$ in the NS interior initially), thus the outcome should be independent of the initial magnetic field strength, because, as [140] argued, initially weak magnetic fields inside the disk should be amplified to values $\sim 10^{15}$ G due to MRI. This expectation is confirmed by the simulations of [95] who find that characteristic values of the plasma parameter β in the disk are $10^2 - 10^3$ (top right panel of Fig. 2), and since characteristic values for the gas pressure in these disks are $P_{\text{gas}} \sim \rho v^2 \sim 10^{30} \text{dyn/cm}^2 (\rho/10^{10} \text{g/cm}^3) (v/0.2c)^2$, the expression $\beta = 8\pi P_{\text{gas}}/B_{\text{disk}}^2$ yields for the magnetic field (B_{disk}) in the disk

$$B_{\text{disk}} \sim 10^{15} \left(\frac{\beta}{100} \right)^{1/2} \left(\frac{P_{\text{gas}}}{10^{30} \text{dyn/cm}^2} \right)^{1/2} \text{G}. \quad (16)$$

Thus, numerical relativity BHNS simulations demonstrate that BHNS mergers are viable progenitors of sGRBs.

4. Simulations of NSNS mergers

It has been 17 years since successful hydrodynamics simulations of NSNS mergers in full general relativity were carried out [175]. Like simulations of BHNSs, simulations of NSNS mergers in which the final outcome is a BH, involve the modeling of physical obstacles like MHD shocks and spacetime singularities, too.

An interesting aspect about NSNS mergers is that the outcome has more options than BHNS mergers. The uncertainties in the nuclear EOS and the fact that current observations allow a large range of nuclear EOSs with Tolman-Oppenheimer-Volkoff (TOV) limit mass $\sim 2.0M_{\odot} - 2.8M_{\odot}$ [101, 129], then depending on the binary total mass the outcome of an NSNS merger could be any one of the following:

- I) If the binary total mass M_{NSNS} is less than the Tolman-Oppenheimer-Volkoff (TOV) limit mass, a massive spinning neutron star that never collapses to a BH will form.
- II) If M_{NSNS} (minus any mass lost to escaping material) is greater than the TOV limit, but less than the maximum mass when allowing for maximal uniform rotation – the supramassive limit (which is typically 20% larger than the TOV limit [122]) – a supramassive NS (SMNS) will form. An SMNS is initially differentially rotating, but due to braking of the differential rotation by magnetic fields (or by viscosity) [166, 48], it will eventually be brought to uniform rotation, and can collapse to a BH (delayed collapse) following spin-down, e.g., due to magnetic dipole radiation.
- III) If M_{NSNS} (minus any mass lost to escaping material) exceeds the supramassive limit, straight after the merger either a BH will form or an HMNS. A threshold mass M_{thres} separates these two possibilities:
 - a) If $M_{\text{NSNS}} > M_{\text{thres}}$, then a BH will form following merger on a dynamical time scale (prompt collapse).
 - b) If $M_{\text{NSNS}} < M_{\text{thres}}$, then a hot, differentially rotating, dynamically stable HMNS will form. The HMNS is transient because a combination of gravitational wave emission, braking of the differential rotation and neutrino cooling will drive its eventual collapse to a BH (delayed collapse).

For work on determining M_{thres} see [174, 171, 21].

As far as sGRBs are concerned, at this time only outcomes II) and III) seem to be relevant, because these are the only ones where a BH-disk engine could potentially emerge. However, numerical relativity simulations have shown that no disk remains outside the BH which forms following the collapse of supramassive neutron stars [169, 167, 11, 12] (see also [111]). This is because the equatorial radius of the SMNS is inside the radius which becomes the innermost stable orbit of the remnant black hole. Thus, at this time, it seems that only type III) outcomes can form a BH-disk engine.

Many years of numerical relativity simulations of binary NSNSs have allowed us to gain a better understanding of the parameter space that leads to these different

outcomes. For a comprehensive review of simulations of NSNS binaries we refer the reader to [68] (see also [46, 13]). Next we will focus primarily on work in full GR related to NSNS mergers as sGRBs.

4.1. Hydrodynamic simulations

Like simulations of BHNSs, the first studies of NSNS-mergers as sGRB engines in full GR focused on cases where a BH-disk system forms after merger, and investigated the potential for an appreciable accretion disk to form outside the remnant black hole. The basic results in this regard have not changed much over the last 10 years, and were summarized in the original studies of irrotational NSNS in full GR in [174] and [171]. There different EOSs and mass ratios were considered, finding that asymmetric NSNS binaries typically have larger disk masses than equal mass binaries, and that disk masses up to $0.06M_\odot$ are possible for mass ratios of 0.75. The authors also derived the following EOS-dependent, and total-mass-dependent fitting formula for predicting the disk mass following BH formation [171]

$$M_{\text{disk}} = M_{\text{disk},0} + A(1 - q)^p, \quad (17)$$

where $q \leq 1$ is the binary mass ratio, $M_{\text{disk},0}$ is the disk mass for $q = 1$, and A , p fit parameters. For the APR EOS [5] with total mass $2.96M_\odot$, the authors find $M_{\text{disk},0} = 4 \times 10^{-4}M_\odot$, $A \approx 1.44M_\odot$, $p = 4$. For the SLy EOS [44] with total mass $2.76M_\odot$, the authors find $M_{\text{disk},0} = 3 \times 10^{-4}M_\odot$, $A \approx 3.33M_\odot$, $p = 3$. The range of applicability of Eq. 17 is restricted to $q \gtrsim 0.8$ [171]. More recent work on this topic [106, 10] is in agreement with the earlier findings, and a different fitting formula for disk mass predictions following the merger of quasi-circular, irrotational (initially $\Gamma = 2$ polytropic) NSNSs was derived in [151]. Disk masses of up to $0.2M_\odot$ were found following asymmetric NSNS mergers in [151]. But, it is currently not known whether such high disk masses are extreme or not. Also, the time at which the disk mass measurement is made is usually somewhat arbitrary. More simulations using different EOSs are necessary to draw definitive conclusions and settle the aforementioned issues. In addition, the impact of the NS spin on the amount of mass left to form a disk onto the BH has not been considered yet, and it is conceivable that spin can make a difference at least when near the threshold mass M_{thres} . However, simulations in full general relativity accounting for the NS spin are still in their infancy (see e.g. [184, 185, 186, 25, 135, 91, 41, 179, 53, 52]). Finally, simulations of eccentric NSNS that form BHs following merger, indicate that disk masses can be up to $\sim 0.27M_\odot$ [81, 54]. Thus, numerical relativity simulations have established that NSNS mergers, too, can form BH-disk engines. But, can jets emerge following an NSNS merger?

Recent hydrodynamical studies of accretion onto a single BH treating neutrinos argue that neutrino annihilation may not suffice to launch jets following a NSNS merger. The reason is that NSNS mergers tend to create very baryon-loaded environments [89]. These results are in agreement with the analysis of [124] who find that the post-merger

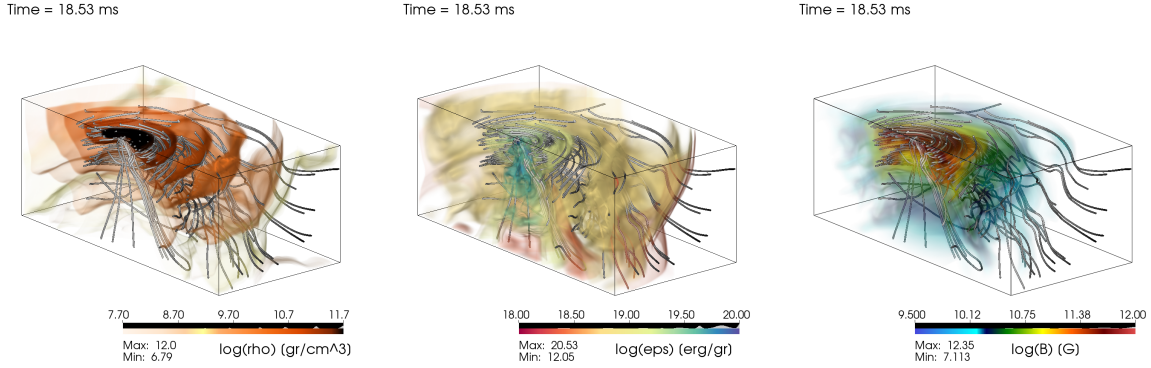


Figure 4. Volume rendering of the rest-mass density (left panel), specific internal energy (middle panel), and magnetic-field magnitude (right panel) of the BH-disk system at $t = 18.3$ ms. The curves indicate the magnetic-field lines. Note that the positive z-axis points downward, and the quadrant shown has dimensions $[0 \text{ km}, 115.8 \text{ km}] \times [-115.8 \text{ km}, 115.8 \text{ km}] \times [0 \text{ km}, 92.16 \text{ km}]$. Figure 7 from [43].

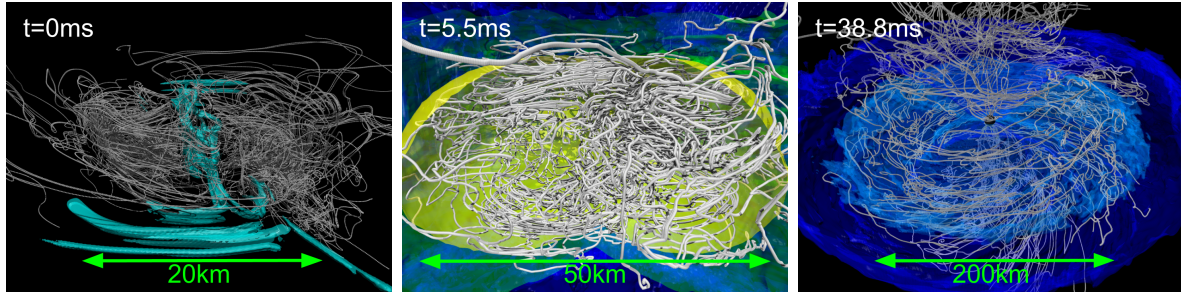


Figure 5. Volume rendering of rest-mass density, magnetic-field strength and magnetic-field lines (white curves) at select times. In the left panel, the cyan color indicates magnetic-field strengths greater than $10^{15.6}$ G. In the middle panel, the yellow, green, and dark blue colors indicate rest-mass densities of 10^{14} , 10^{12} , 10^{10} g/cm^3 , respectively. In the right panel, the light and dark blue indicates rest-mass densities of $10^{10.5}$ and 10^{10} g/cm^3 , respectively. Figure 1 from [97].

fall-back material can “choke” a BH-disk jet engine. In [89] it was also argued that while the environments around BHNS mergers are not as baryon-rich, and collimated outflows can be launched via neutrino processes, they concluded that neutrino annihilation is an inefficient jet acceleration mechanism. Hence, [89] concluded that if jets do emerge following compact binary mergers, then MHD processes should play a major role in driving them.

However, the magnetic field must be able to overcome the inertia of the matter in order to launch a jet, and achieving magnetic-field dominance in the dense environment surrounding a NSNS merger remnant is not trivial. One can estimate how strong the magnetic field near the BH has to be, by equating the magnetic energy density with the rest-mass energy density of the merger remnant atmosphere. Relativistic NSNS simulations demonstrate that characteristic rest-mass densities around the remnant are

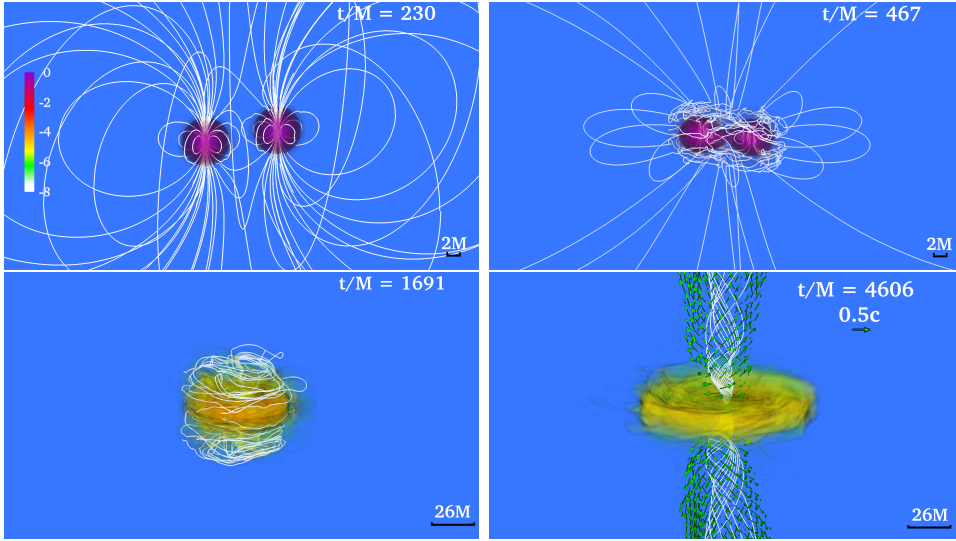


Figure 6. Same as in Fig. 3, but here $\rho_{0,\max} = 5.9 \times 10^{14} (1.625 M_{\odot}/M_{\text{NS}})^2 \text{ g cm}^{-3}$ and $M = 1.47 \times 10^{-2} (M_{\text{NS}}/1.625 M_{\odot}) \text{ ms} = 4.43 (M_{\text{NS}}/1.625 M_{\odot}) \text{ km}$. The appearance of an organized, large scale magnetic field inside the incipient jet is clear in the bottom right panel. Figure 1 from [160].

$\rho_0 \sim 10^9 \text{ g/cm}^3$. Thus, the relation $B^2/8\pi \gtrsim \rho_0 c^2$ yields

$$B \gtrsim 10^{15} \left(\frac{\rho_0}{10^9 \text{ g/cm}^3} \right)^{1/2} \text{ G}. \quad (18)$$

But, how can a typical pulsar magnetic field be amplified from an initial value of $10^{10} - 10^{12} \text{ G}$ on the NS surface to 10^{15} G ? In the next session we address this question and discuss whether BH-disk engines formed in NSNS mergers can launch jets through magnetic processes.

4.2. Magnetohydrodynamic simulations

The Newtonian simulations of [155] reported that the Kelvin-Helmholtz instability (KHI) naturally occurs in the shearing layer at the collision interface during an NSNS merger. The KHI development has also been confirmed in NSNS simulations in full GR [8, 154]. Following [155], the Newtonian simulations of [148] discovered that *the development of the KHI at merger can generate magnetar-level magnetic-field strengths within 1 ms*. Local special relativistic ideal MHD simulations have confirmed this picture [196], and some works have adopted subgrid models to simulate this effect in global NSNS simulations in full GR [80, 133]. Self-consistent simulations in full GR of this effect were carried out in [96], where unprecedentedly high resolution was adopted and was found that the KHI and the MRI occurring during and shortly after merger amplify the magnetic fields in the HMNS to rms values of $10^{15.5} \text{ G}$ within $\sim 5 \text{ ms}$. Thus, it is fairly established that at least for equal mass NSNS mergers the combination of KHI and MRI are the principal hydromagnetic processes through which the magnetic field

can grow to values capable of launching jet outflows even before the star may collapse and form a BH-disk engine.

Early long term ideal MHD simulations of NSNS mergers in full GR [8, 106] reported no jet launching. On the other hand, a subsequent ideal MHD calculation of binary NSs in full GR reported the formation of “jet-like structures” [152]. This means the formation of a funnel-like structure, but not the emergence of a collimated, Poynting-dominated outflow. The same result was also found in recent resistive MHD simulations of NSNS mergers in full GR [43] (see Fig. 4). A more recent full GR ideal MHD study of NSNSs [97] did not find a jet or an ordered poloidal field (see Fig. 5), and concluded that the ram pressure of the fall-back material is so strong that, in contrast to BHNSs [95], not even a wind can be launched after BH-disk formation. More recent ideal MHD NSNS simulations in full GR [58] do not report jets or the appearance of a large scale, ordered magnetic field following merger. However, the initial magnetic field strengths are low and the adopted resolution is not high enough to capture the magnetic field growth due to KHI and MRI.

Motivated by the successful jet launching in the BHNS calculations of [140], [160] adopted similar methods as in [140], but this time in a NSNS setting, focusing on the same binary configuration as the one evolved in [152]. About ~ 60 ms following merger, incipient jets emerge even in this NSNS scenario (see Fig. 6). The authors also performed a comparison study with an identical case where the initial magnetic fields were confined in the interiors of the stars. The study showed that jets are launched for interior only magnetic fields, too, and on the same time scale. Consistent with the findings of [97] the authors found that a jet is launched only after the density of the fall-back matter above the BH has decreased to levels where $B^2/(8\pi\rho c^2) \gg 1$. The disk lifetime in the simulations of [160] was estimated to be ~ 0.2 s, and the jet Poynting luminosity 10^{51} erg/s, which are again consistent with typical sGRBs. The magnetization in the incipient jet outflow found in the simulations was $B^2/8\pi\rho c^2 \sim 100$, which implies that the terminal Lorentz factor of these jets can reach $\Gamma_L \sim 100$ to explain sGRB phenomenology. The success of launching jets both with interior only and interior/exterior magnetic fields was attributed to the fact that the magnetic fields in the scenario where an HMNS forms, can be amplified to magnetar levels before collapse to a BH takes place.

Eq. (15) for a 10^{16} G magnetic field on a $2.8M_\odot$ BH with spin $\chi = 0.7$ – the values found in [160] – predicts a BZ power of

$$L_{\text{BZ}} \approx 10^{52} \left(\frac{\chi}{0.7} \right)^2 \left(\frac{M_{\text{BH}}}{2.8M_\odot} \right)^2 \left(\frac{B_{\text{BH}}}{10^{16}\text{G}} \right)^2 \text{erg/s.} \quad (19)$$

Thus, the electromagnetic luminosity found in the simulations is close but does not match the BZ power. Nevertheless, this mismatch could be due to insufficient spatial resolution or the approximate nature of Eq. (19), or the more baryon loaded environments surrounding NSNS merger remnants where Eq. (19) may not be applicable.

We note, here, that unlike the other MHD studies of NSNS mergers in full GR, the authors of [160] seeded the initial neutron stars with dipole magnetic fields which are

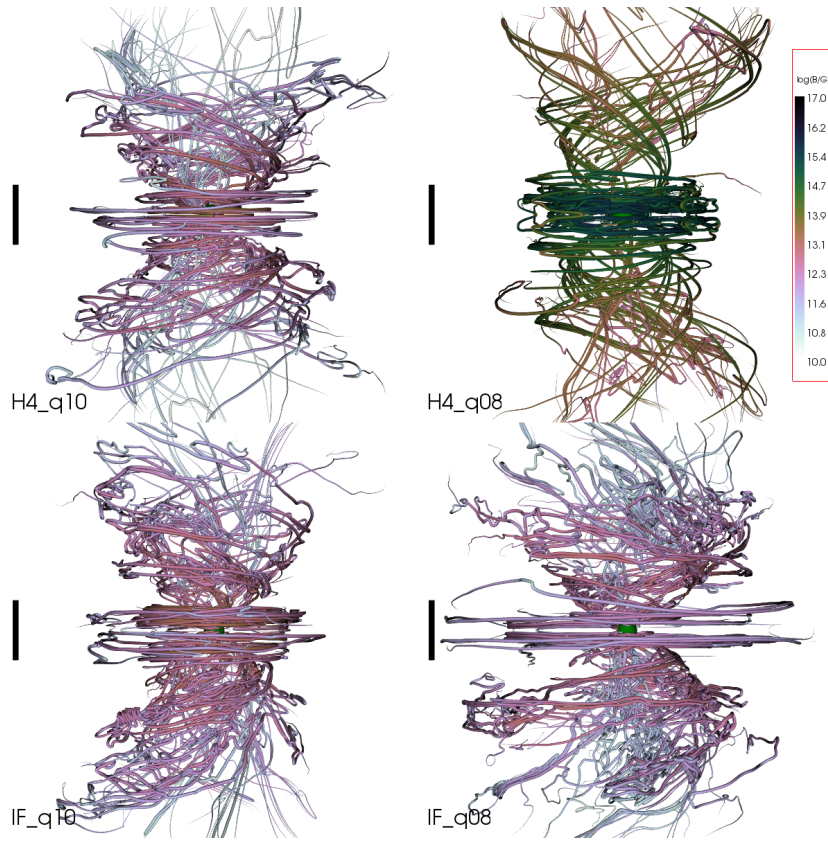


Figure 7. Magnetic field lines ~ 32 ms following merger for different initial NSNS models. H4 and IF stand for different EOSs studied in, and “q10” (“q08”) indicate a mass ratio of 1.0 (0.8). The black vertical lines indicate a length scale of 20 km. The color represents the magnetic field strength ($\log_{10}(|B[G]|)$). Figure 16 from [92].

high in comparison with typical inferred magnetic field strengths of pulsars in NSNS binaries. However strong, they were still dynamically unimportant initially, and offered a natural means for generating equipartition-level magnetic fields in the post-merger remnant, as is anticipated for dynamically stable HMNSs because of the KHI and MRI effects. Thus, what [160] argued is that if the KHI and MRI have enough time to amplify the magnetic fields prior to collapse, then an incipient jet can emerge following collapse to BH.

A more recent work [92] performed a large suite of magnetized NSNS simulations in full GR with magnetic fields restricted in the stellar interiors initially, and varying the orientation of the magnetic dipole moment (aligned/antialigned with orbital angular momentum), the EOS and the mass ratio. The authors report that their results confirm the emergence of an ordered magnetic field (see Fig. 7), but that longer evolutions are required for jet emergence.

Finally, it is important to clarify that there are two effects at play following collapse of a dynamically stable HMNS, but secularly unstable, that in a sense are competing from the point of view jet launching. One effect is that the density in the funnel decreases with time as the fall-back material within the funnel is accreted onto the BH.

The other effect is that at the same time the disk is being accreted onto the BH. If the disk is accreted before the density of the fall-back material in the funnel has decreased sufficiently, then an sGRB jet will not be possible. Thus, a successful magnetically powered jet requires that the density in the funnel drop well below a critical value (at which $B^2/8\pi\rho_{\text{crit}}c^2 = 1$) on a time scale that is shorter than the disk accretion time scale. Note that different EOSs change not only the disk mass, but also the amount of ejected and fall-back matter. Thus, for a given amount of disk matter generated after NSNS mergers with different EOSs, a magnetically powered jet may not be possible for any EOS because of potentially different amount of fall-back material. However, neutrino annihilation should help in lowering the density in the funnel. Thus, a combination of neutrino and magnetic processes could potentially launch jets in cases where the fall-back material time scale is long.

5. Conclusions and future challenges

Over the last 10 years numerical relativity simulations of BHNS and NSNS mergers have significantly augmented our understanding of how these compact binaries may form BH-disk engines. It is now well-established that BH-disk systems are a generic outcome of compact binary mergers involving neutron stars. However, forming a BH with an accretion disk is only a necessary requirement to explain sGRBs in the model of a hyperaccreting BH model which drives twin jets that expand at highly relativistic velocities (a leading model for sGRBs). A second necessary condition to establishing theoretically that BHNS and NSNS are viable progenitors of sGRBs (in the hyperaccreting BH model) is to show that the BH-disks their mergers give birth to can launch jets. Recent simulations in full GR have allowed us to study the impact of magnetic fields and assess whether jets can be launched from these engines. The general consensus is that following merger a large scale ordered magnetic field can emerge that is in principle able to drive a collimated, magnetically dominated outflow – a jet. So far, the only works demonstrating self-consistent jet launching following merger have been presented in [140] for BHNS mergers and in [160] for NSNS mergers. These simulations integrated for much longer times than other numerical simulations where magnetic fields are amplified to magnetar-level strengths following merger. At this time, it appears that BH-disk systems formed following a BHNS merger can launch magnetically powered jets only if the initial NS is endowed with a magnetic field that extends from the interior out to the exterior. On the other hand, BH-disk systems formed following a NSNS merger can launch magnetically powered jets when the initial NS is endowed either with interior only magnetic fields or with magnetic fields extending from the interior out to the exterior. However, the choice of surface magnetic-field strength in [140, 160] was larger by a couple of orders of magnitude when compared to typical pulsar magnetic fields. This choice was justified based on the post-merger expectations for magnetic-field amplification by the Kelvin-Helmholtz and magnetorotational instabilities. While the jet emergence in [140, 160] should as a result be independent of the initial magnetic-

field strength (because their strong fields were still dynamically unimportant initially), these calculations must be revisited with weaker initial magnetic fields. Doing so would require much higher resolution (almost 10 times higher) to be able to properly capture all hydromagnetic processes. Adopting such high resolution would render these simulations impractical with current methods and computer resources. However, as methods become more accurate, codes are developed to scale better, and with computer technology advances, long-term high-resolution simulations should be within reach within the next decade. Moreover, it is very challenging to evolve accurately magnetic fields in low density environments with ideal MHD codes. Thus, the calculations adopting magnetic fields that extend from the NS interior all the way out to the NS exterior should also be revisited with more sophisticated methods. Maybe a resistive MHD approach would be suitable, but such schemes in full GR have been developed [130, 42] only recently, and studies of BH-disk jet engines for sGRBs with resistive MHD are completely in their infancy. However, given that from a theoretical standpoint force-free electrodynamics is a subset of ideal MHD [112, 142], in principle, one should be able to develop an ideal MHD algorithm that can evolve accurately both magnetically-dominated and matter-dominated environments at the same time.

At this point, it is important to note that several sGRBs have richer phenomenology than just the gamma-ray burst. For example, about 1/3 of the sGRBs demonstrate strong “afterglow” activity for an extended time [77]. A complete theoretical model should be able to explain the full range of phenomenological features sGRBs have, and perhaps explaining the burst is the easy part. To this extend, simulations of compact binaries in full GR have revealed that these systems exhibit richer phenomenology than just launching a burst [104, 137, 132, 134, 146] having both “precursor” and “aftermath” EM signals. Thus, simulations are already providing opportunities to think about sGRBs in a different way than the “standard” paradigms. Nevertheless, the sGRB phenomenology remains poorly understood, and if we understand it, it could provide discriminating power to choose among the different models. It could also be that different sGRBs have different progenitor systems.

Despite the tremendous developments in the study of compact binary mergers as sGRB engines, many open questions still remain and represent challenges for the next generation of compact binary simulations in full GR. Here we give an incomplete list of such questions: Are the incipient jets found so far stable and do they persist for an accretion time? What mechanism powered these magnetically dominated jets? The BZ effect is a likely candidate, but results so far, while strongly suggestive [140], are not conclusive. How are these incipient jets accelerated to $\Gamma_L \gtrsim 100$? How do jets shine in gamma rays? Is the internal shock mechanism [114, 102] realized? What is the role of neutrinos? Can the neutrino effective bulk viscosity and drag quench the magnetic-field growth due to MRI in a HMNS (see e.g. [86] and references therein)? Can compact binary mergers account for the subclass of sGRBs with extended X-ray emission (see e.g. [77, 76, 157, 84]) or are other sGRB models necessary (see e.g. [109, 118, 31, 36, 153] and references therein)? What can we infer from the time delay between an observed

GW signal and EM signal? What is the correct, hot, nuclear EOS? How can we combine GW and EM observations to better infer the correct EOS?

As a side discussion, we recall that there are other progenitor models of sGRBs that have been proposed and have not received much attention in the numerical relativity community, yet. For example, the merger of a BH with a white dwarf (WD) was proposed in [88], as was the accretion-induced collapse of WDs in [188]. Moreover, we note that sGRBs could be powered following massive white dwarf – neutron star (WDNS) mergers, if the remnant collapses to form a BH. On the other hand, if a massive neutron star is the merger outcome, then it may power a gamma-ray flash [159]. Preliminary studies in full GR suggest that the NS-disk remnant of a WDNS merger is supported against collapse through a combination of additional thermal pressure, due to shock heating, and centrifugal support from the rapid differential rotation [138]. However, following cooling and angular momentum redistribution the remnant can collapse to form a BH-accretion disk system [139, 136] that may power a gamma-ray burst. If this scenario is realized, the GRB would not take place shortly after merger as is expected in a BHNS or NSNS merger, but on the much longer cooling and angular momentum redistribution time scales. Nevertheless, it is not clear yet whether this possibility can materialize because, at least for intermediate mass white dwarfs, nuclear burning after merger is anticipated unbind some fraction of the WD debris (see e.g. [115, 70, 110] and references therein).

Finally, if the recent tantalizing Fermi detection of a hard X-ray signal 0.4 seconds after the merger of the binary black hole event GW150914 [37], which was consistent with sky location of GW150914, was not a chance coincidence, then it would suggest that stellar-mass binary black hole mergers also could take place in a circumbinary magnetized disk. Preliminary GRMHD studies of accretion disks onto equal-mass binary black holes [69, 83, 82] predict that $\sim 1000M$ following merger there is a boost in the Poynting luminosity of the jet outflows observed from these systems. Interestingly, for $M = 65M_\odot$ –the inferred total mass of GW150914– the time scale to the luminosity boost is $1000M \sim 0.3$ s, i.e., *very close to the delay time between the GW150914 peak amplitude and the Fermi signal*. Future observations will show whether the recent Fermi detection was a chance coincidence, and if not, whether accreting BHBH systems can explain such short-EM-burst-like events.

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